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DENSITY VERSUS STABILITY

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DENSITY VERSUS STABILITY*

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Someone is supposed to have said, "Other things being equal, the densest mixtures are the best." Diligent search has failed to reveal the source of this pronouncement but presumably it was made by an authority because many engineers apparently believe something of the sort. There is no particular harm in this viewpoint and it is not altogether incorrect, but it seems that some may be prone to forget that the question of density in a paving mixture is often less important than are other properties.

After years of striving for maximum density in Portland cement concrete, paving engineers in particular are now seeking to include definite quantities of entrained air, an expedient that has not yet been employed in bituminous paving mixtures. However, there is evidence to show that when carried too far, reducing the air voids in an asphalt pavement may result in other undesirable developments - loss in stability, for example.

As in most cases where differences of opinion appear to exist concerning the significance or nature of physical phenomena, some of the differences undoubtedly arise over understanding of terminology so perhaps a few terms should be discussed and their real

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meaning explored. In describing the properties of bituminous paving mixtures, there are three different terms often used which are definitely related but which are not necessarily synonymous. These terms are density, permeability and compaction. A fourth term, stability, is neither related nor synonymous.

Density

The density of homogenous masses is usually indicated and expressed by the specific gravity which means the ratio between a unit volume of the substance or material in question and an equal volume of water under specified conditions of pressure and temperature. In the case of bituminous mixtures the compacted mass of the finished pavement or of the laboratory test specimen normally contains three ingredients and often four.

These ingredients are:

1. The mineral aggregate
2. The asphaltic binder
3. Air
4. Water

The volume of the whole is equal to the sum of the volumes of the separate ingredients. The most significant and directly comparable relationships between the quantity of aggregate, quantity of asphalt and quantity of air present is indicated by the direct volume relationships. However, in the practical business of manufacturing and controlling paving mixtures, volumetric methods have been found to be unsatisfactory and generally inaccurate, therefore, engineers have almost universally expressed these relationships based upon the weight of the ingredients, and while this method is beyond question the most satisfactory and reliable it does tend to disguise the true and most significant relationship which is only indicated by the volumes of the several ingredients that compose a bituminous paving mixture. Figure 1 illustrates both diagrammatically and by numerical percentage values the weight and volume relationships that exist in a typical paving mixture.

In discussing paving mixtures, another unidentified individual has argued that a mass of solid stone represents the most stable condition in which the material can exist and therefore when fitting the fragments together, the more nearly one could reproduce the density of the original monolithic mass, the more nearly would the combination reproduce the original high "stability." This argument might have some merit if it were possible to reproduce the powerful bonds by which the mineral particles are held together. One is reminded of the nursery rhyme recounting the tragedy that befell Humpty Dumpty. All the King's men could not put him together again. It is obvious that asphalt paving technologists are reduced to the expedient of trying to cement the particles together by means of a relatively weak binder in the form of petroleum residues or asphaltic "cement." This means that any section through a bituminous paving mixture represents a series of discontinuities that extend in all directions. As the rock particles should be hard enough and tough enough to withstand the crushing loads of pneumatic tired traffic, any movement which occurs within the mass must take place between the adjacent particles which may be in direct physical contact or which may be more or less separated by lubricating films of asphalt.

The relationship between the volume of solid matter and the total apparent volume occupied by the combined mixture is usually referred to as the "relative density" and the obvious fact that the asphalt must occupy some of the space between the aggregate particles has led to two different methods or theories of design.* The older school of asphalt paving technologists were generally inclined to base the percentage of asphalt upon the voids in the mixture and many advocated that the amount of asphalt should be the quantity required to fill all the voids. This practice may have been acceptable in earlier years when vehicle loads were much lighter and much less numerous than is the case today, but the practice did give asphaltic pavements a bad reputation for being slippery and dangerous when wet.

During the development of the road mix type of surfacing in California over 25 years ago, considerable attention was given to the development of methods or formulas for determining the most satisfactory amount of road oil or liquid asphalt. It was evident that the maximum amount that could be tolerated was considerably less than the volume of voids in the mixture. California adopted the surface area formula in 1930 and about ten years later the CKE determination was added to the procedure and these methods are still in use. In this method of design, no attention is given to the density of the mixture except to be sure that the air voids in the compacted mixture are not less than three per cent and preferably four per cent or more. Most paving engineers today have learned that it is very unwise to use enough

*The design of an asphalt paving mixture means selecting the type and gradation of aggregate, then determining by test, by calculation or by guess the type and amount of asphaltic binder.

asphalt to fill all the voids in the mixture and many specifications include some limiting clause which regulates the amount of asphalt depending upon the void space available. There appears to be ample evidence to prove that the most reliable and most universally applicable basis for estimating the optimum amount of asphalt is to evaluate the surface capacity of the aggregate particles. While an examination of a section taken from a compacted asphalt pavement may seem to indicate that the voids are completely filled with asphalt, a close scrutiny of the freshly prepared mixture before compaction clearly shows that the process of "mixing" results in a more or less uniform film or surface coating on each particle. Therefore, if the amount of surface to be coated is known and the acceptable thickness of film is also known it is then possible to form a very close estimate of the amount of asphalt that will be required. This method has the practical advantage that the essential data can be derived from sieve analysis and tests on the aggregate prior to compaction whereas the voids cannot be determined until after the correct amount of asphalt has been added. The designer using the void "theory" is, of course, frustrated by the fact that he cannot determine the amount of asphalt until the void volume is known.

Most paving engineers and highway maintenance engineers have observed that asphaltic pavements often appear to be satisfactory and stable for a period of time, perhaps for several years, and then finally develop evidence of instability in the form of grooving, surface waves, or other distortion.

There are, of course, several contributing factors which may be responsible for this delayed change in appearance. It requires time for instability to become evident where a very viscous or low penetration asphalt is involved. It is also true that in certain cases the mineral aggregates may break down or degrade, producing more fines and in effect changing the mix composition. But a third cause is the increase in density caused by traffic compaction.

Permeability

Many engineers have seemed to feel that if paving mixtures were dense it would follow that they would not be porous or permeable. Paving engineers are generally concerned with permeability only as it may influence the passage of water. The passage of water or any other liquid through the capillary channels of a porous mass is retarded by the internal friction of the liquid which is commonly called "viscosity," and the size of the individual pores becomes a very pertinent factor and this size is not reliably indicated by the usual "density" determination. For example, the void ratio of a finely divided clay mass may exceed .5 yet clay cores are placed in earth dams to prevent the percolation of water through the dam. On the other hand, concrete sand and similar materials having a void ratio less than .5 may have a coefficient of permeability thousands of times that of clay. It should be obvious that if the engineer wishes to produce an impervious pavement it is not necessarily or obviously accomplished by reducing the total void space. On the other hand, for a given material, permeability and density are not necessarily at variance.

Compaction

Judging from the general comments and methods of using the term, the word compaction is often used more or less interchangeably to mean "density" although all engineers are aware that certain combinations of aggregates with or without an artificial binder may go together quite easily to form dense masses low in air voids. If such mixtures are dense, it does not necessarily follow that they have been "compacted" to any appreciable degree and it is also true that bituminous mixtures of this type are often not particularly stable. On the other hand, certain types of aggregates, for example Ottawa sand, can be subjected to a considerable compressive force or compactive effort with little or no measurable change in the density. It is equally true that coarse crushed stone can be compacted or at least subjected to considerable compactive effort with the result that stability will be high but density may be low. This is also a well-known characteristic of the open graded or macadam type mixtures which are not lacking in compaction or in stability but definitely could not be regarded as dense, and such mixtures are generally porous or permeable as well.

Stability

In order to explore the existence or lack of a relationship between density and stability, it is necessary to identify the properties of a mixture that affect or contribute to stability. The word stability is applied in many fields and has so many different shades of meaning that it has come to be little more than a descriptive term such as "good" or "permanent."

However, asphalt paving technologists generally know what they mean by the term "stability" and as we are talking about plastic mixtures, stability means the ability to resist deformation. In view of the fact that asphaltic paving mixtures consist of two principal ingredients, namely, aggregate and asphalt, it is logical that the properties of both contribute to any resistance value or "stability" which the mixture may possess. Because of the marked differences in character between particles of stone and films of asphalt, it is further logical that the influences and effects of each will be different. Carrying the analogy further, because the mineral aggregate represents from 80 per cent to 90 per cent of the volume, it is not surprising that factors influencing the properties of the aggregate are usually the most important.

In the absence of asphalt, a mass of mineral aggregate, whether sand or crushed stone, will resist deformation or change in shape only because of frictional resistance between adjacent particles and also, of course, due to inertia. All asphalts used in paving work are viscous liquids at 140°F. and perform very obediently according to the classical laws of hydrostatics or hydraulics. Viscosity is a term meaning that liquids have internal friction and the laws governing liquid friction are quite different and almost diametrically opposite to those that govern frictional resistance of solid bodies in contact.

Since Coulomb's time, engineers dealing with soil mechanics or the mechanics of granular materials have recognized the importance of friction and of a property which has been called "cohesion" and the authors of this paper are for the moment completely orthodox and recognize that these are the fundamental properties that enable a mass composed of granular particles and a viscous liquid to resist deformation under load. Amontons' law states that the resistance to movement of solid particles in contact varies with the nature of the surfaces and in proportion to the pressure with which they are forced together but is independent of the speed. The performance of liquids having high internal friction or viscosity is usually described by referring to the movement of two plates separated by the liquid in question. Under these conditions, the resistance of the liquid is virtually independent of pressure but varies directly with the area and directly with the speed of movement.

Years of investigation and masses of test data have brought forth little evidence that bituminous paving mixtures disobey these laws. However, as the two laws are quite different, it follows that masses of dry aggregates will tend to obey Amontons' law very closely and this tendency will also persist in dry mixtures with a low asphalt content. As the asphalt content increases, however, a gradual transition takes place until a condition is reached where the amount of asphalt exceeds the void space and all particles are separated by a film of asphalt.

When this condition is reached, the laws governing liquid friction or viscosity take over completely and all paving engineers will recognize that when the voids are over filled with asphalt an asphaltic pavement will flow and move about readily under vehicle wheel loads.

However, it may be pointed out in passing that all unstable pavements may not inevitably become roughened. In fact, in former years some asphalt paving technologists definitely recommended mixtures with plenty of soft asphalt so that the surface would "iron out under traffic." Compositions of this sort undoubtedly have their uses but they cannot be classed as stable pavements. Therefore, recognizing that interparticle friction is the major property that contributes to stability, it must then be recognized that this property is largely independent of the contact area between particles. In paving mixtures this accounts for the fact that aggregate gradation has little predictable influence and adequate stability may be developed in mixtures composed of a wide variety of particle size combinations.

On the other hand, the cohesive element is due almost entirely to the asphaltic binder and the resistance of viscous liquids is influenced by the area in contact; therefore, it logically follows that an increase in surface area or an increase in the viscosity of the binder all will greatly increase that portion of the resistance generally described as "cohesion." As the basic laws also state that the resistance of viscous liquids is proportional to the speed of action, the rate of loading becomes an important consideration. It seems unnecessary for the design engineer or paving technologist to divert his attention or complicate the picture by worry over such things as interlock, shearing forces, particle interference, etc., as these are only manifestations or variants which derive their effects from the basic resistance factors commonly described as friction and cohesion.

However, because of the different laws that govern these two properties, the mechanics of bituminous mixtures can become complicated enough but a consideration of these laws does furnish an adequate explanation for some well-known and incontrovertible facts which may be somewhat categorically stated as follows:

> Stable asphaltic paving mixtures can be constructed almost regardless of the aggregate gradation.
>
> Stable mixtures can be constructed with any grade of liquid asphalt ranging from SC-2 road oil to 20 penetration or lower paving asphalt.
>
> Asphalt pavements high in asphalt may distort badly under slow moving traffic but may remain quite smooth and satisfactory under high speed traffic.
>
> For standing loads in parking areas, an asphaltic pavement has little if any greater supporting capacity than the same thickness of sand and gravel without the asphalt.

It is the primary purpose of this paper to illustrate some of the changes in stability which develop simply through increased compaction alone. In 1937 the first kneading compactor was constructed and placed in operation in the laboratory of the California Division of Highways. This compactor was designed and built for the express purpose of making it possible to simulate the kind and degree of compaction that is developed in a typical pavement under traffic. An investigation of the density that existed in California pavements showed quite clearly that there is usually a small but definite increase with time and that asphaltic pavements several years old are generally more dense than those that have been newly constructed.

At that time it was more or less taken for granted that increasing compaction would improve the stability and there was concern lest the laboratory compactor produce specimens that had greater stability than could be developed on the road. (It is now well-known that the tendency of laboratories to overload or overcompress test specimens has been almost universal.) Therefore, the kneading compactor was operated to form a test specimen 2-1/2 in. high and 4 in. in diameter having density and stability corresponding to an asphaltic pavement that had been under traffic for one year. It appeared that this could be accomplished by applying 150 applications of the tamper foot under a load of 500 psi. The compactor applied pressure to an area equal to one-fourth of the specimen surface permitting the material to move or shift while avoiding damaging impact.

In order to show something of the relationships involved, a recent series of bituminous mixture test specimens were formed by use of the kneading compactor in the laboratory of the University of California. The effects of the following variables were explored to some degree:

Different types of mineral aggregates (3)

A range of pressures beneath the foot of the kneading compactor (200 to 600 psi)

The effect of double plunger compaction at 2000 psi

Different percentages of asphalt binder.

The influences on the following properties were noted:

Stability, i.e., interparticle friction measured by the Hveem Stabilometer

Tensile resistance of the mass measured by the Cohesiometer

Specific gravity of the compacted mixture

Percentage of air voids calculated.

Three types of aggregates were selected for a series of comparative tests. These materials were:

1. Crushed granite from Watsonville, California
2. Crushed quartzite from Richmond, California
3. Uncrushed screened gravel from Livermore, California.

The Watsonville and Richmond materials contained no rounded nor water worn particles. The Livermore gravel contained no crushed particles. All were combined to give approximately the same gradation corresponding to a normal dense graded mixture.

The data shown on the charts, Fig. 2 to 10, bring out first the significant differences in the shapes of the density curves (mass specific gravity) compared to the shapes of the curves of Hveem stability versus asphalt content for each of the three aggregates of different type but similar grading. These differences in test results are more marked for the specimens prepared by kneading compaction compared to those compacted by the double plunger method.

It may be noted that specimens produced by the kneading compactor gave maximum stability values at asphalt contents lower than the amounts required to produce maximum density of the specimens.

In addition, these figures indicate that there are also significant differences in the positions and shapes of Hveem stability curves for each of the aggregates depending on the method used to compact the test specimens. In all cases the specimens prepared by double plunger (previously spaded and leveled) have about the same stability value regardless of asphalt content, whereas the specimens prepared by kneading action drop markedly in stability for the richer mixes which of course agrees with common experience on actual pavements. Close inspection of Fig. 4, 7 and 10 reveals that the densities of the briquettes compacted under a static load of 2000 psi are consistently lower than those produced by kneading compaction using only 500 psi. Therefore, for the two methods of compaction, the density-stability relation in the low asphalt content range is just the opposite of what it is in the higher ranges of asphalt content.

Attention is directed to the 8 per cent ordinate on Fig. 2, 3 and 4 which indicates the same density and the same cohesiometer value but the stabilometer values are quite different from the different methods of compaction.

A further inspection of Fig. 3, 4, 6, 7, 9 and 10 shows that a more consistent relationship exists between the density and the tensile strength as evidenced by the parallelism between the cohesiometer curves and the mass specific gravity or "density" curves. Another significant effect produced by the method of compacting a specimen is illustrated by the large increases in cohesiometer values as a result of the kneading type compaction (Fig. 3, 6 and 9). This increase is more nearly in accord with cohesiometer values on specimens cut from actual pavements. The evident similarity of slope for the cohesiometer and density curves is a clue to the real significance of the density factor, if any. In other words, density may influence cohesion but any test that reflects cohesion primarily will have a poor correlation with pavement stability.

In order to eliminate the variations in density produced by different proportions of asphalt and aggregate, a decision was made to prepare specimens of different densities from mixtures of uniform composition. In order to do this mixes of selected compositions were molded in duplicate using the kneading compactor at each of the following pressures: 200, 300, 400, 500, and 600 psi. Standard mixing and curing procedures were followed. Figures 11, 12 and 13 represent the test results obtained on these series of samples for the same three aggregates heretofore described.

The compositions of the mixes subjected to the varying compaction pressures were judiciously selected to secure both stable and unstable specimens in the stabilometer. This was done by selecting appropriate asphalt contents from the Hveem stability versus asphalt content curves of Fig. 2, 5 and 8. Two asphalt contents were selected for both the Watsonville and Richmond aggregates. For the Livermore material three asphalt contents were used.

In general, the results obtained indicate that up to a point density increases with compactive effort, although beyond a certain value changes in density are not detectable by ordinary means. (Fig. 11, 12 and 13) On the other hand stability values for these mixes of constant composition varied greatly, both increasing and decreasing in magnitude, depending on the asphalt-aggregate ratio of the mix. The specimens with low asphalt content increased in both stability and density with increasing compactive effort, while those with high asphalt content decreased in stability and increased in density. No simple relationship between density and stability is apparent from these data.

In order to further examine the effects of density, the percentage of air voids was calculated and is shown in comparison with the other data on Fig. 11, 12 and 13.

It is evident that stabilometer values sharply decline on these mixtures when the air voids are reduced below 4 per cent and in general stabilometer values are very low or nonexistent when the calculated air voids indicate 2 per cent or less.

The fact that density should not exceed 96 per cent or 97 per cent is well-known to most practical paving engineers but is not demonstrated by any of the "stability testing" devices that are markedly influenced by cohesion or viscosity effects--the cohesiometer for example.

Conclusion

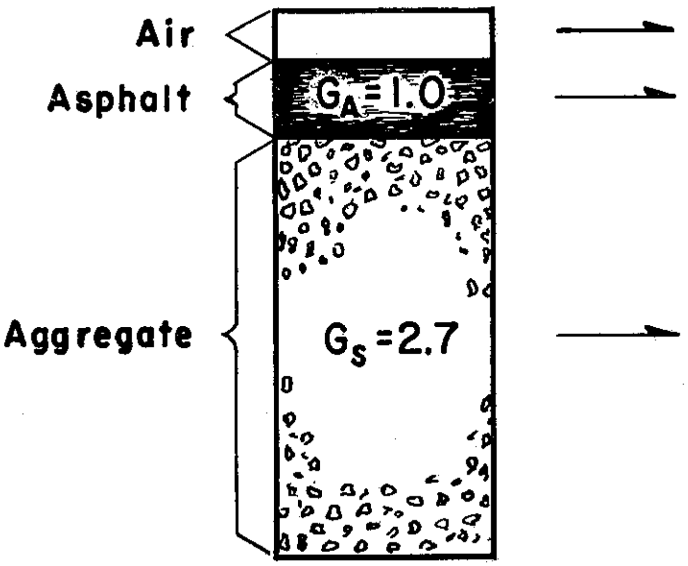
From the evidence of these and other test data as well as evidence furnished by pavement performance, there is no general relationship between density and stabilometer values. However, the same data indicate that there is a general relationship between the density of a paving mixture and the cohesive or tensile resistance of the mass.

Tests made in the California laboratory over a period of nearly 20 years show that there is no dependable direct or consistent correlation between test procedures such as the cohesiometer and the performance of pavements. Therefore, any test results that correlate well with the cohesiometer cannot be expected to correlate with pavement performance.

There is a very high degree of correlation between stabilometer results and pavement performance and little correlation between stabilometer and the density of the mixture except that the stabilometer results are invariably low when the void spaces are filled or nearly filled with asphalt.

Example Illustrating Volume-Weight Relationships in a Batch of Asphaltic Concrete

Diagrammatic Composition



Compacted Weight 151 pcf

Relative Proportions			
By Weight			By Volume
Batch	% of Agg	% of Total	% of Total
0	0	0	3.1
100	5	4.76	11.5
2,000	100	95.24	85.4
2100	105	100	100

Fig 1

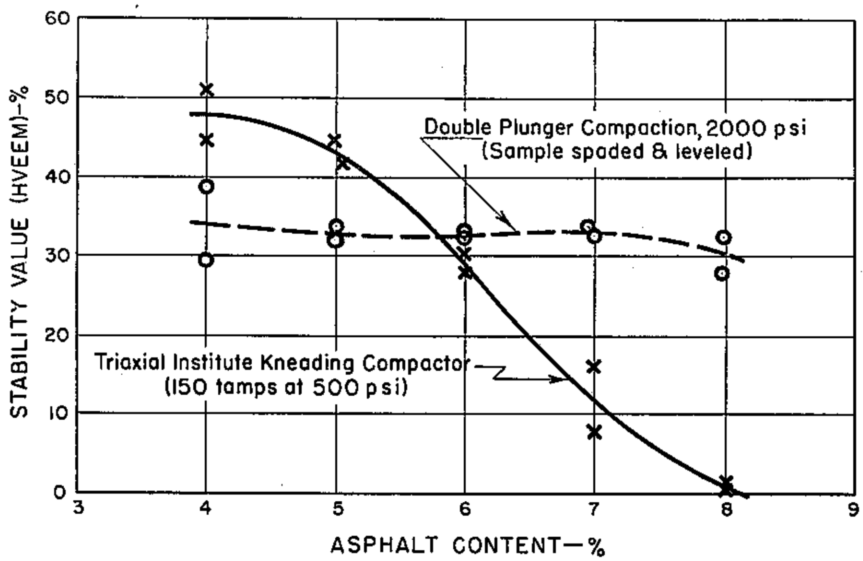


Fig 2 Watsonville Crushed Granite

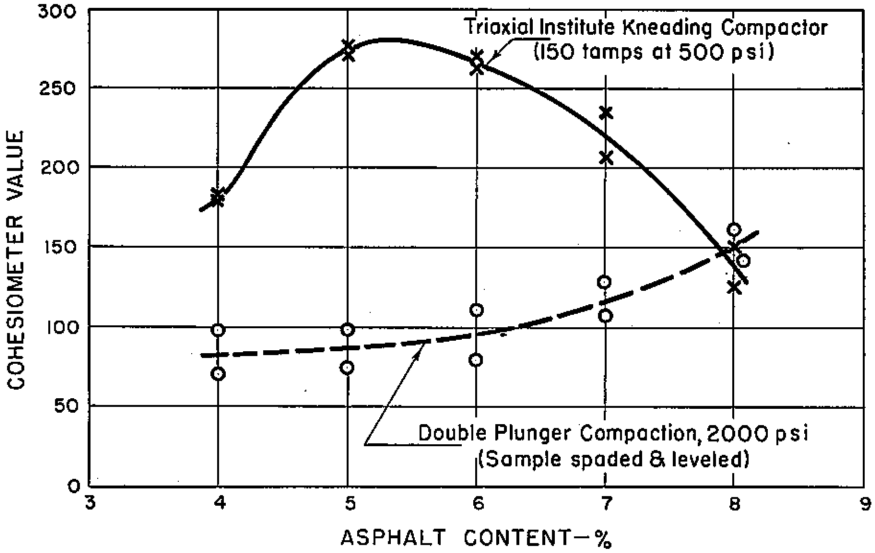


Fig 3 Watsonville Crushed Granite

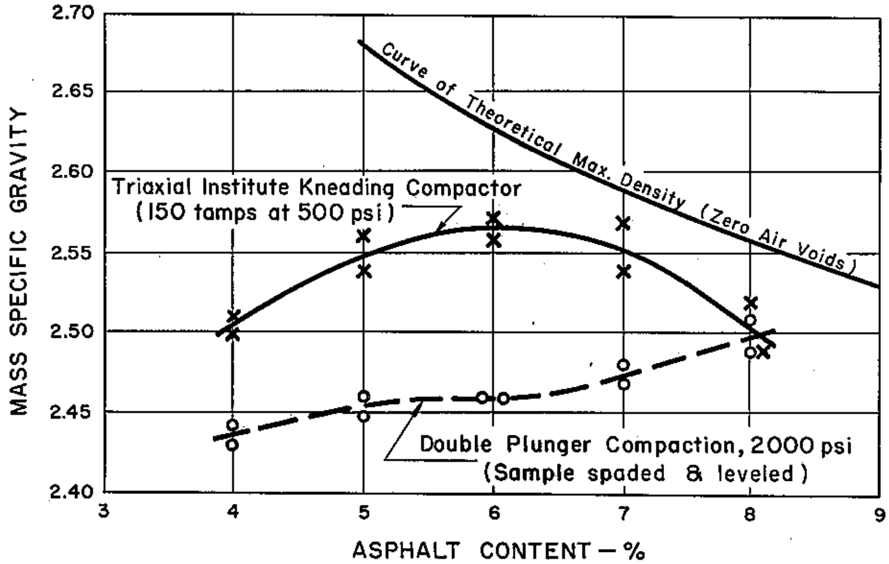


Fig 4 Watsonville Crushed Granite

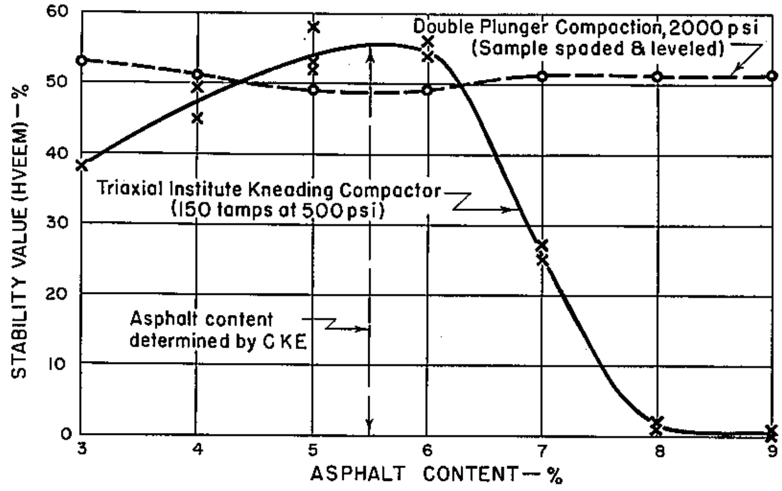


Fig 5 Richmond Crushed Quartzite

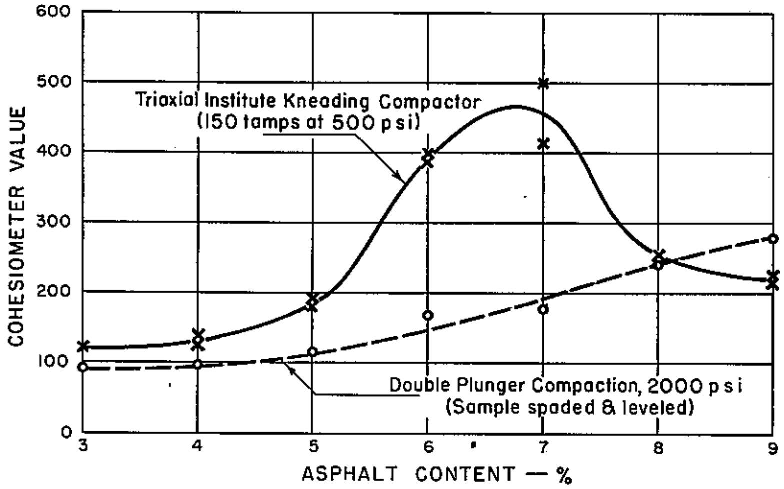


Fig 6 Richmond Crushed Quartzite

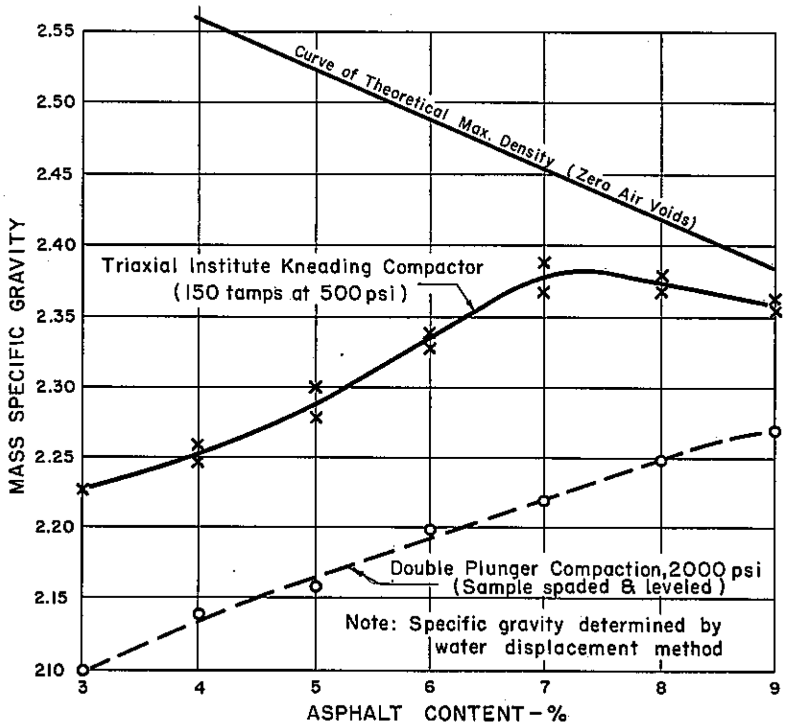
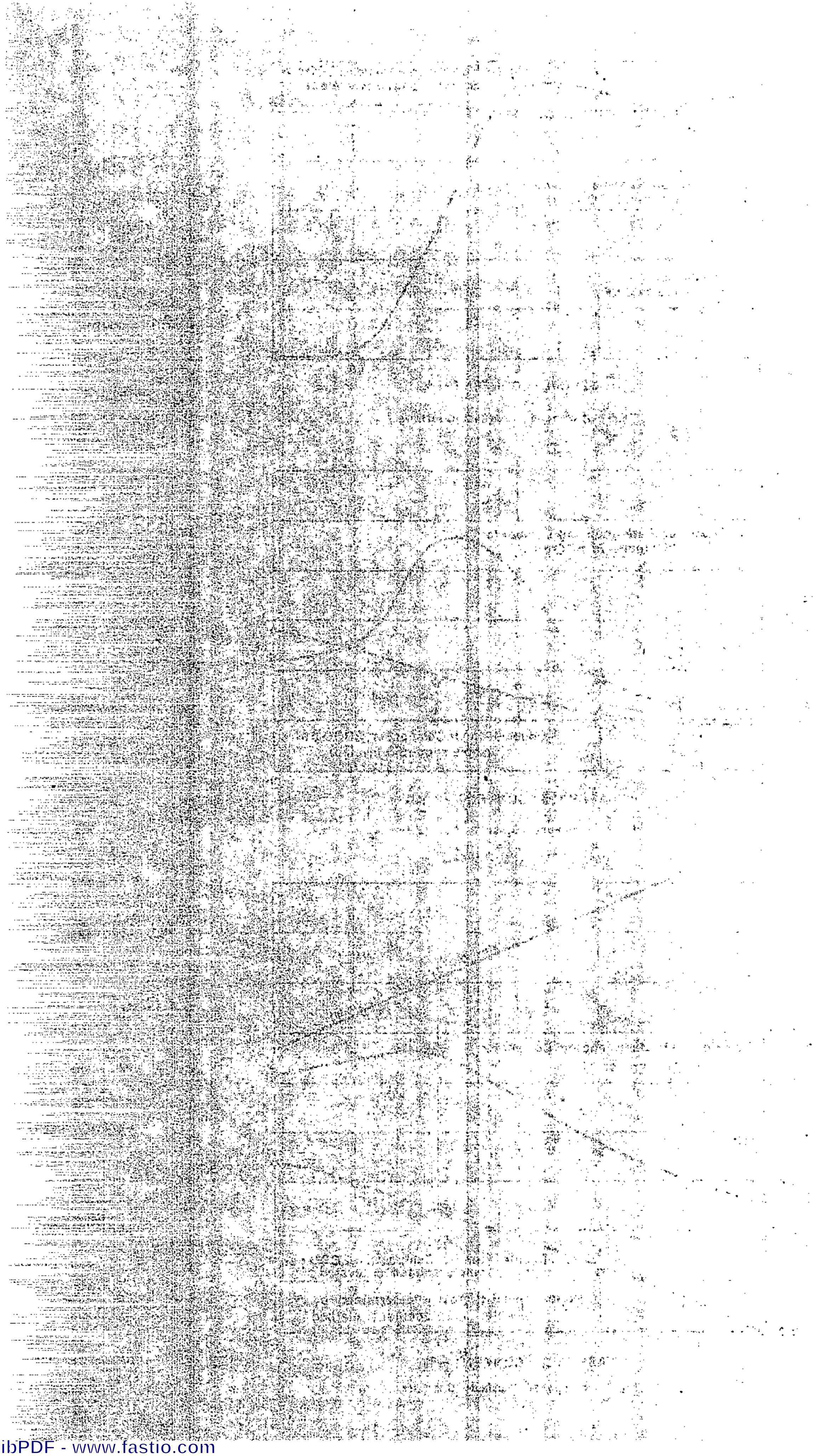


Fig 7 Richmond Crushed Quartzite



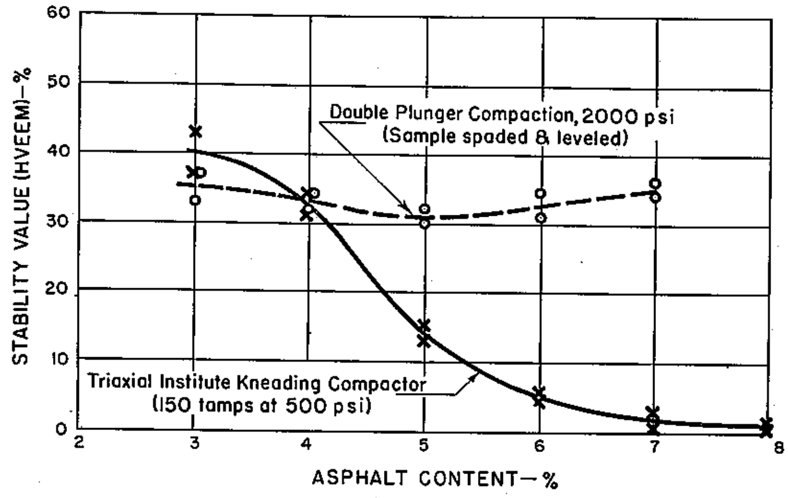


Fig 8 Livermore Gravel

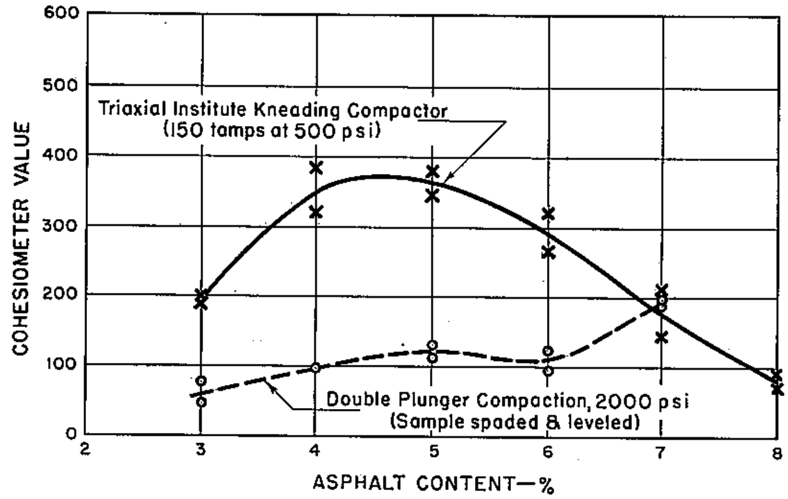


Fig 9 Livermore Gravel

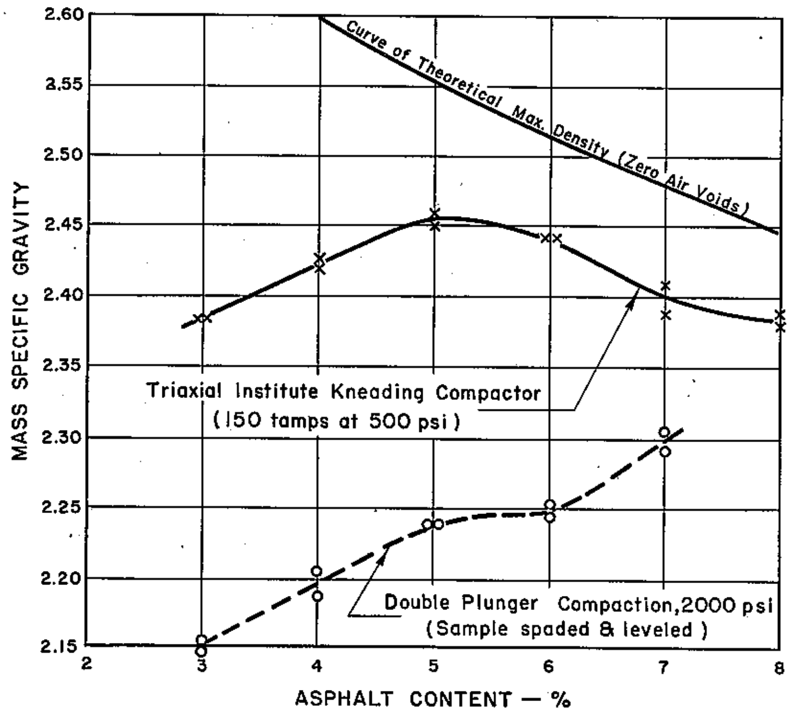
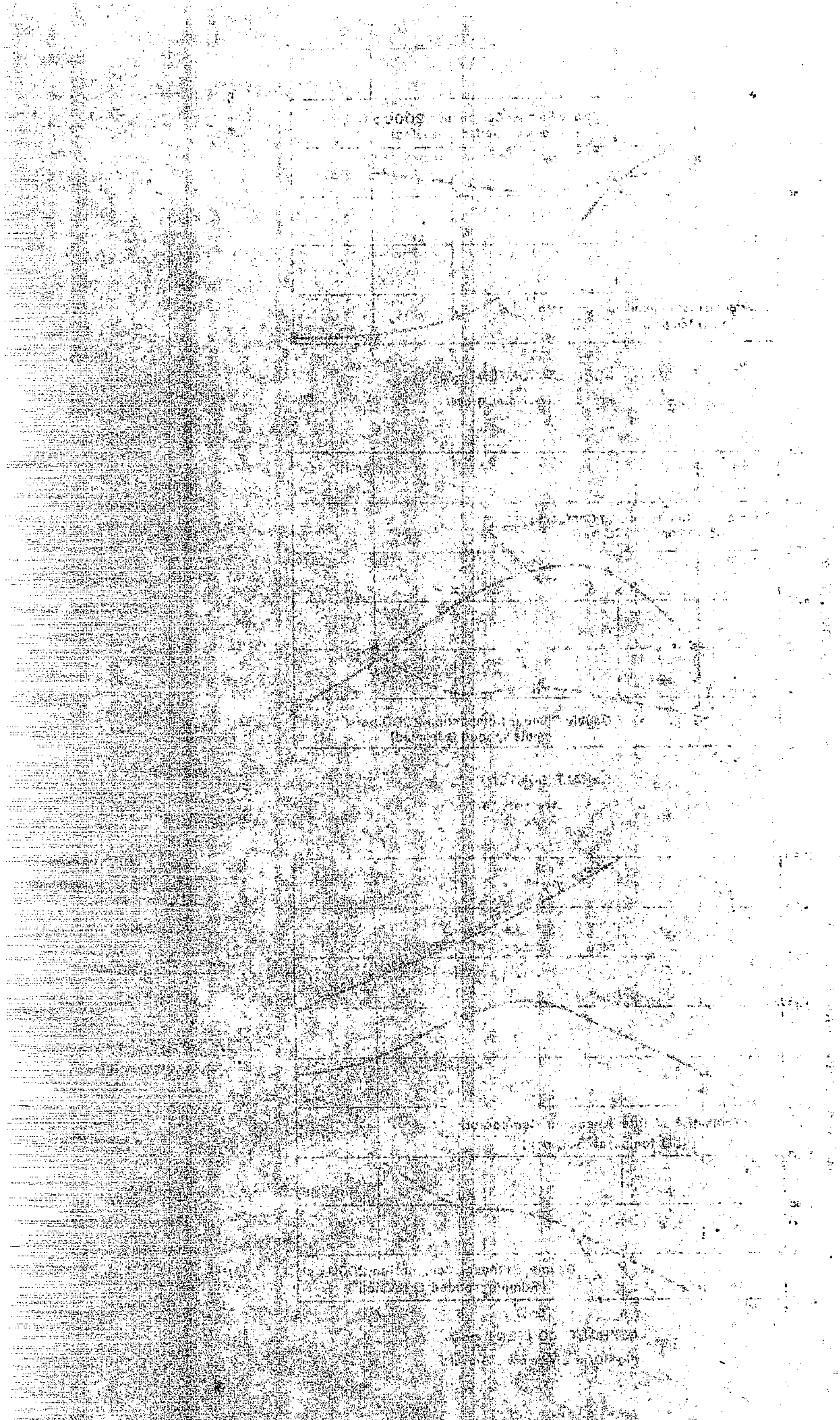


Fig 10 Livermore Gravel



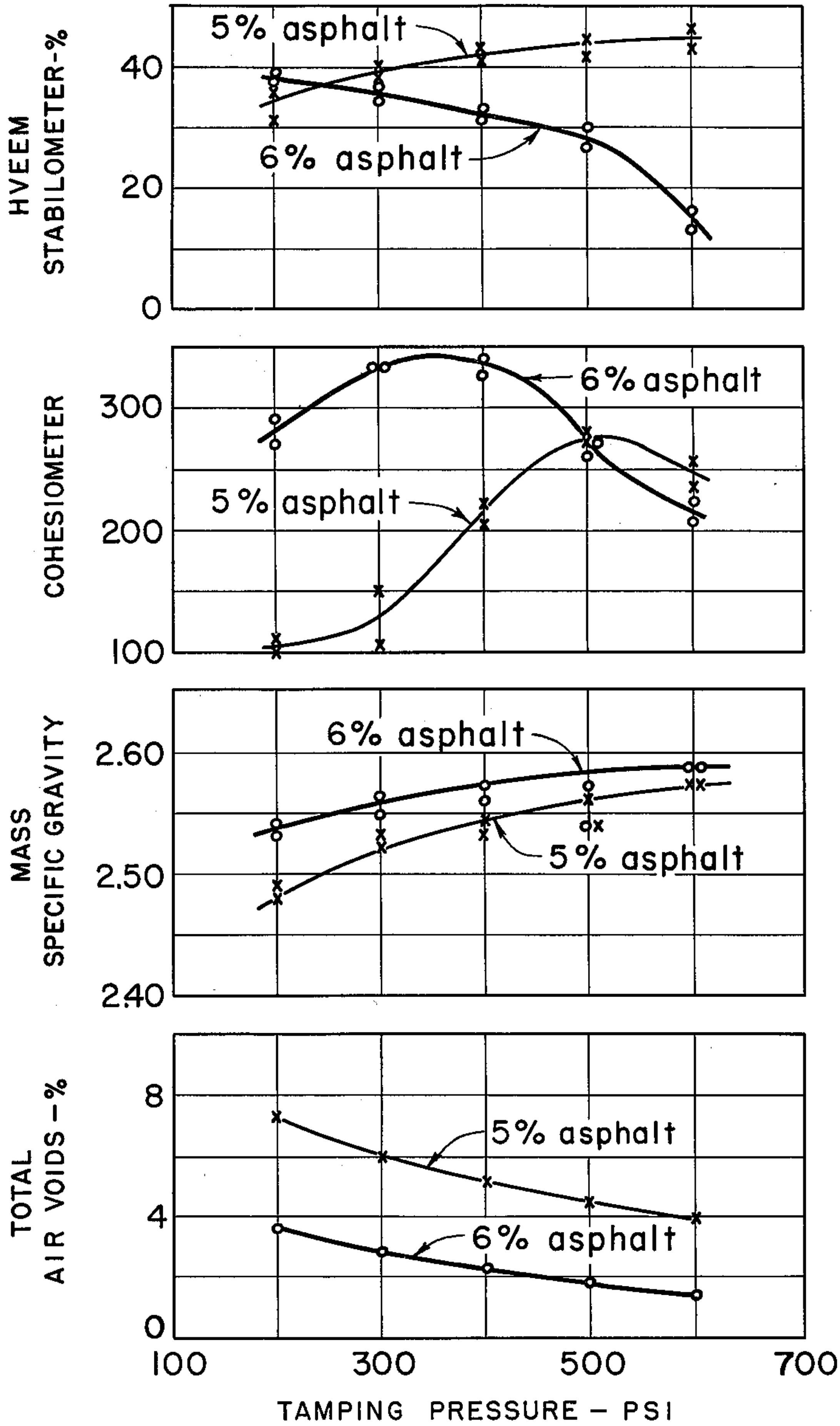


Fig 11 Watsonville Crushed Granite

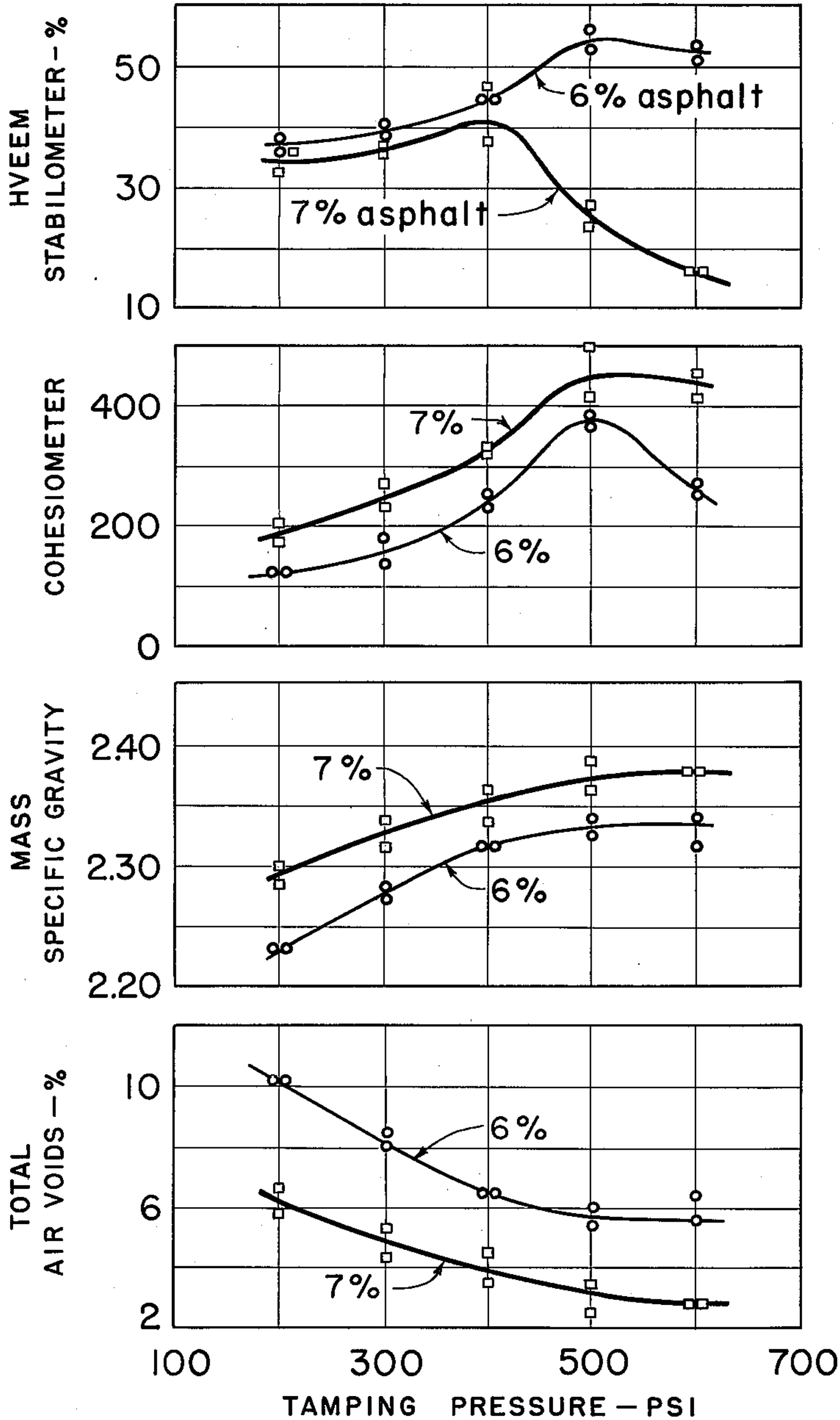


Fig 12 Richmond Crushed Quartzite

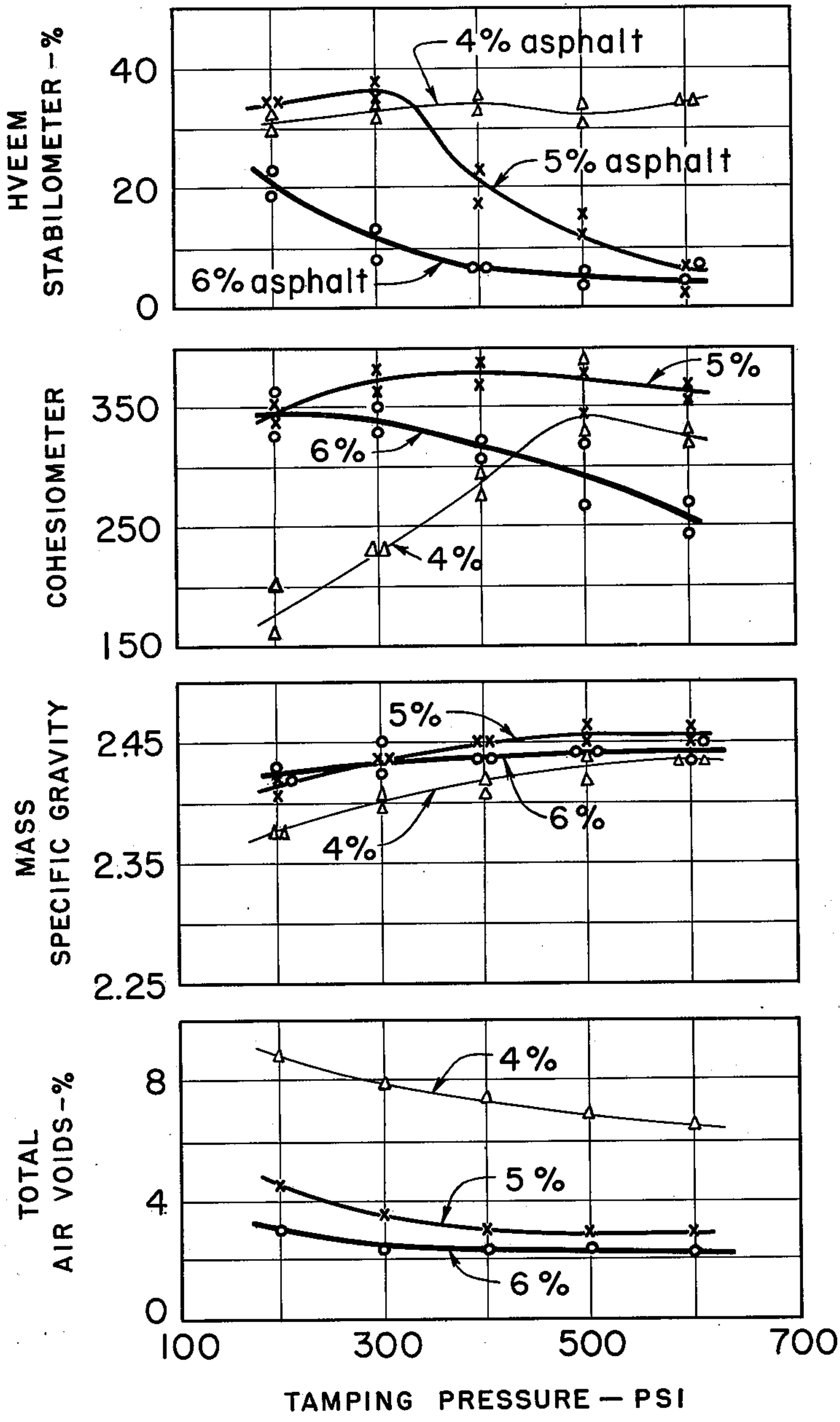


Fig 13 Livermore Gravel